AN INVESTIGATION OF THE LONGITUDINAL HANDLING QUALITIES OF A VARIABLE STABILITY FLIGHT SIMULATOR

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THESIS

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ABSTRACT

An investigation of the longitudinal handling qualities of the variable stability flight simulator, converted from a C-11B Instrument Flight Trainer, found the qualities to be an unrealistic representation of aircraft motion. Non-linearities found in the dc servo drive circuits were caused by the dc servo drive motor's starting voltage, striction, misalinement of the motor and reduction gear axles, potentiometer resolution, and gearing backlash. The equations of motion for the T-33 aircraft were simulated with the analog portion of a hybrid computer.

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TABLE OF SYMBOLS

C_D	drag coefficient, D/q_oS
C_{D_o}	drag coefficient at $\alpha = 0$
$C'_{D_\alpha}, C'_{D_{\alpha^2}}$	curve fitting drag coefficients for drag polar curve [Ref. 3]
C_L	lift coefficient, L/q_oS
C_{L_o}	lift coefficient at $\alpha = 0$
C_{L_α}	lift coefficient proportional to α (1/deg)
$C_{L_{\delta_E}}$	lift coefficient proportional to δ_E (1/deg)
D	drag force (lb)
g	acceleration of gravity (32.2 ft/sec^2)
Δh	altitude change (ft)
$\dot{h}$	$\frac{dh}{dt}$, rate of climb (ft/sec)
I_x, I_y, I_z, I_{xz}	Airplane moments and products of inertia about body axes (slugs-ft^2)
L	lift force (lb)
m	mass of aircraft (slug)
M_b	pitching moment about y-body axis (ft-lb)
M_α	pitching moment coefficient proportional to α (1/sec^2-deg)
$M_{\dot{\alpha}}$	pitching moment coefficient proportional to $\dot{\alpha}$ (1/sec-deg)
M_q	pitching moment coefficient proportional to q (1/sec-deg)

M_{δ_E}	pitching moment coefficient proportional to δ_E $(1/\text{sec}^2\text{-deg})$
n_z	normal acceleration, positive in pull up (g)
p_b, q_b, r_b	angular velocities about x, y, z-body axes respectively (deg/sec)
$\dot{q}_b$	$\frac{dq}{dt}$ (deg/sec^2)
q_o	dynamic pressure, $= \frac{1}{2}\rho V_o$ (lb/ft^2)
S	wing area (ft^2)
t	time (sec)
T	thrust (lb)
u_s, v_s	velocities along x and y-stability axes respectively (ft/sec)
$\dot{u}_s$	$\frac{du}{dt}$ (ft/sec^2)
V	airspeed (ft/sec)
V_o	initial airspeed (ft/sec)
ΔV	airspeed change (ft/sec)
ΔV_{ias}	indicated airspeed change (kts)
ΔV_{kts}	airspeed change (kts)
$\dot{V}$	$\frac{dV}{dt}$ (ft/sec^2)
X_s, Z_s	forces along x and z-stability axes respectively (lb)
α	angle of attack (deg)
$\dot{\alpha}$	$\frac{d\alpha}{dt}$ (deg/sec)
α_T	angle of thrust vector (deg)

β	angle of sideslip (deg)
δ_E	elevator deflection (deg)
δ_{ES}	elevator stick deflection (volt)
θ_b	pitch angle (deg)
$\dot{\theta}_b$	$\frac{d\theta_b}{dt}$ (deg/sec)
ρ	air density (lb/ft)
ϕ_b	roll angle (deg)
τ	time constant (sec)

$D_o = q_o S C_{D_o}$ $\quad\quad D_{\Delta V} = 2q_o S C_{D_o}/V_o$

$D_\alpha = q_o S C_{D_\alpha}$ $\quad\quad D_{\alpha\Delta V} = 2q_o S C_{D_\alpha}/V_o$

$D_{\alpha 2} = q_o S C_{D_{\alpha 2}}$ $\quad\quad D_{\alpha 2\Delta V} = 2q_o S C_{D_{\alpha 2}}/V_o$

$L_o = q_o S C_{L_o}$ $\quad\quad L_{\Delta V} = 2q_o S C_{L_o}/V_o$

$L_\alpha = q_o S C_{L_\alpha}$ $\quad\quad L_{\alpha\Delta V} = 2q_o S C_{L_\alpha}/V_o$

$L_{\delta_E} = q_o S C_{L_{\delta_E}}$

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The author wishes to express his appreciation to Mr. Robert Limes and Mr. William Thomas for their assistance on the hybrid computer, to Professor Donald Layton for his assistance and advice while pursuing this project, and especially to his wife, Kathee, for her patience and understanding during the investigation of the simulator and preparation of this thesis.

I. INTRODUCTION

This investigation is the third in a series of reports on the modification of the Link Aviation model C-11B "Jet-Propelled Aircraft Instrument Flying Trainer." The modification was instituted in the Aeronautical Engineering Department of the Naval Postgraduate School in 1967.

The C-11B trainer was acquired for the purpose of modifying the trainer to a flight simulator for use as an aid for class demonstrations on flight characteristics and a research vehicle for thesis projects. The trainer was originally built to provide instrument training to pilots. It did not simulate any particular aircraft nor did it have the ability to change characteristics. To be useful to the Aeronautical Engineering Department, the simulator had to be capable of having its characteristics varied so that various aircraft could be simulated and their characteristics could be compared. If a simulator is capable of these changes it is called a variable-stability simulator.

A flight simulator is a "good" simulator if it realistically represents the flight conditions that a pilot encounters in an aircraft. The addition of many instruments, a cockpit, aircraft noise, motion cues, and visual cues all aid in giving the pilot a believable flight experience. The additions also contribute significantly to the cost of the simulator. The C-11B trainer had the

instruments familiar to the pilot, the cockpit, and provisions for noise generation, but not the visual and motion cues. It was decided that the addition of visual and motion cues were not needed at this time for the C-11B trainer to become a variable-stability, fixed-base simulator.

Lieutenant J. A. Johnson reported on his investigation of the feasibility of modifying the trainer in Ref. 1. In Ref. 2, Lieutenant Commander C. J. Sweeney described the conversion of the trainer to a flight simulator be replacing the electronic components with solid state devices and solving the equations of motion with a hybrid computer. The computer is composed of a high speed digital computer model 9300 manufactured by Scientific Data Systems of Santa Monica, California and an electronic analog computer model CI 5000 manufactured by COMCOR, Ind., of Anaheim, California.

This report deals with the investigation of the longitudinal flying qualities of the simulator which are dependent on the electronic, mechanical, and servo elements of the simulator. The flying qualities of the simulator allow the pilot to be the closing link in the control loop. The pilot actuates a control in the simulator and the control data is changed to an electrical input for the computer. The computer solves the aerodynamic equations of motion using the control data input and the aircraft's characteristics and sends the solutions back to the simulator for the deflection of the cockpit instruments. The pilot observes the instruments and makes the appropriate

control movements to perform the maneuver he desires. If the computer does not solve the equations correctly, or the instrument dials do not indicate the computer's solutions, the pilot must make additional control movements that are not normally required. The requirement for extra movements is caused by the poor flying qualities of the simulator and could result in the pilot forming incorrect opinions of the flight characteristics that are being tested.

Using data for the T-33 aircraft, the flying qualities of the simulator were investigated in two parts: first, the comparison of the expected solutions to the equations of motion with the solutions using the analog portion of the hybrid computer, and second, the observation of the cockpit representation of the computer's solutions. The investigation was conducted at the Naval Postgraduate School, Monterey, California, during the period January 1969 through June 1969.

II. COMPUTER

During modification of the trainer, the vacuum tube amplifiers used for the solution of the equations of motion were removed with the intention of finding another method to solve the equations. Instead of designing and building solid state amplifiers to fit into the simulator, it was economically and operationally feasible to use the hybrid computer facilities of the Naval Postgraduate School to solve the motion equations. The computer also offered a very rapid method of varying the characteristics of an aircraft, either manually or by a precomputed program. The instrument calibration factors for converting voltages to dial deflections were easily accomplished on the computer.

A. FORCE AND MOMENT EQUATIONS

Four axes systems are commonly used in writing the equations of motion: inertia, body, wind, and stability. Each system is a right-hand Cartesian coordinate system with all but the inertia system having its origin at the center of gravity, c.g., of the aircraft. The inertia system is fixed in inertia space having its origin on the earth's surface and the x-axis fixed in the direction of true north. The body axes have the x- and z- axes fixed in the plane of symmetry and the x-axis in the direction of the aircraft's nose. The wind axes have the x- and

z-plane rotated to have the x-axis in the direction of the velocity vector. The stability axes are between the body and wind axes with the x-stability axis the projection of the x-wind axis into the plane of symmetry. The rotation angle of the x-body axis to the x-stability axis is the angle of attack, α, and the rotation angle of the x-stability axis to the x-wind axis is the sideslip angle, β. The body, stability, and wind axes are related to the inertia axes system with the Euler angles of pitch, θ, roll, ϕ, and yaw, ψ. Body and stability axes relationships are shown in Figure 1 and the axes relationship with the Euler angles are shown in Figure 2.

Three of the four axes systems were utilized for the longitudinal equations in the computer: the body axes for the moment equation and the Euler angles, the stability axes for the force equations, and the inertia axes for the altitude and rate of climb. The full equations [Ref. 3] are:

Moment Equation About y-Body Axis

$$M_b = I_y \dot{q}_b + (I_x - I_z)\, p_b r_b - I_{xz}\, (r_b^2 - p_b^2)$$

Force Equations in x-and z-Stability Axes

$$X_s = m[\dot{u}_s - v_s(r_b \cos\alpha - p_b \sin\alpha) + g(\sin\theta_b \cos\alpha - \cos\theta_b \cos\phi_b \sin\alpha)]$$

$$- T\cos(\alpha + \alpha_T)$$

$$Z_s = m\,[v_s\,(p_b \cos\alpha + r_b \sin\alpha) - u_s\,(q_b - \dot{\alpha})$$

$$- g(\cos\theta_b \cos\phi_b \cos\alpha + \sin\theta_b \sin\alpha)] + T\sin(\alpha + \alpha_T)$$

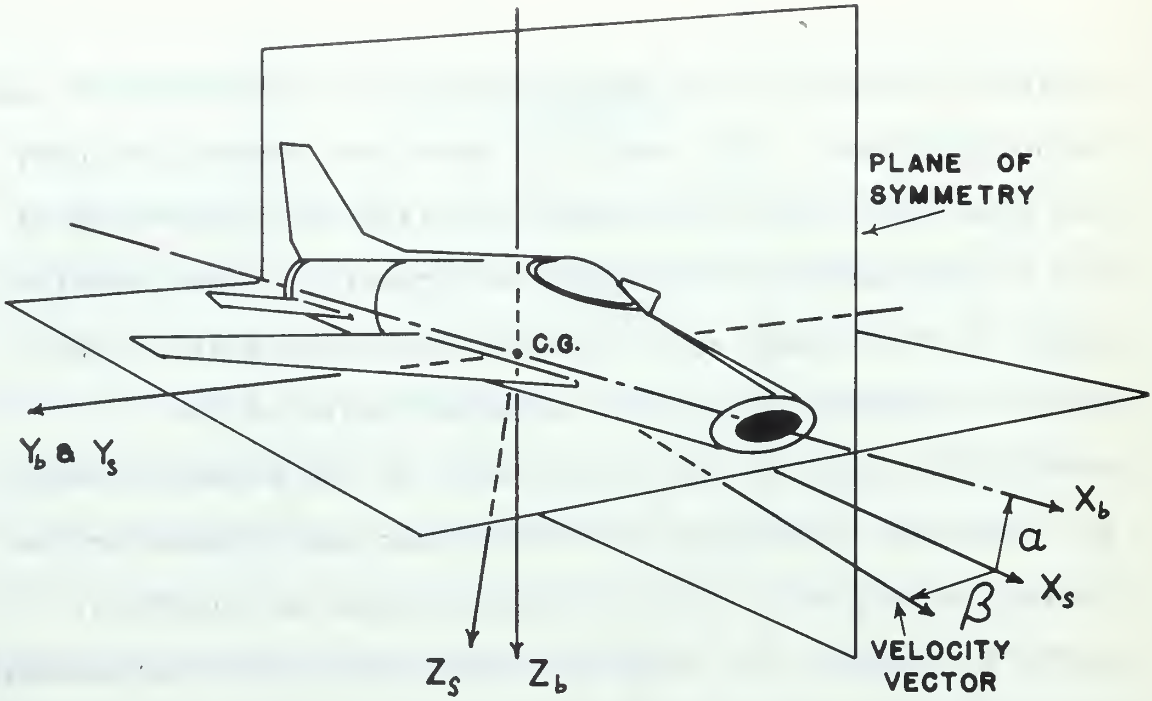

FIGURE 1. RELATION OF BODY AND STABILITY AXES

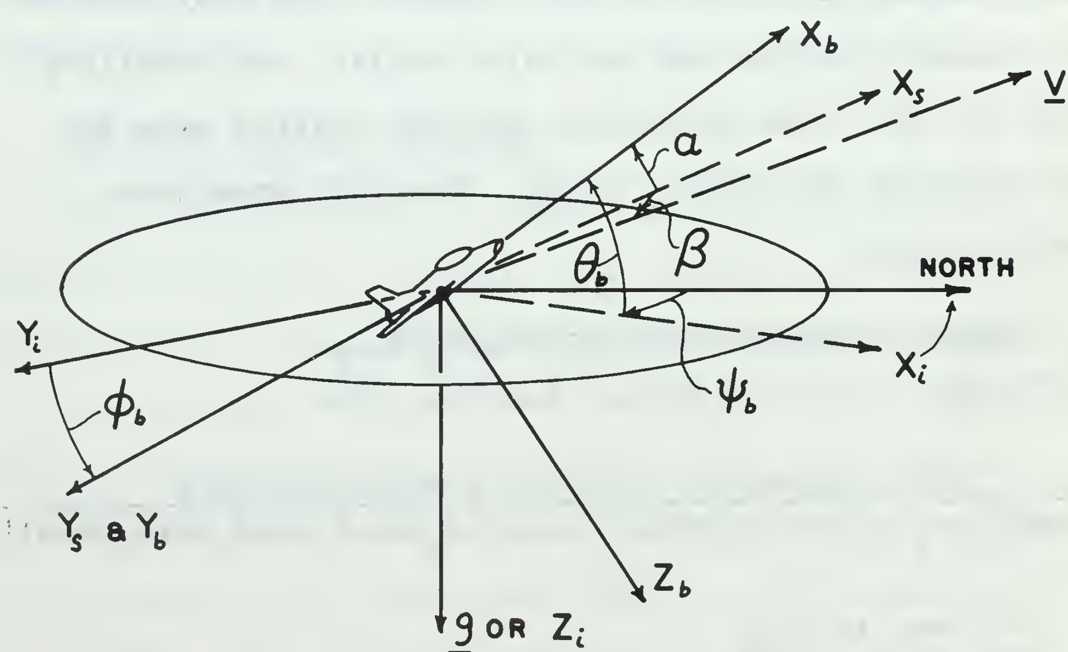

FIGURE 2. MASTER DIAGRAM OF EULER ANGLES AND AXIS SYSTEMS USED IN SIMULATION

Euler Angles in x - z Body Axes Plane

$$\dot{\theta}_b = q_b \cos \theta_b - r_b \sin \phi_b$$

Height in z-Inertia Axis

$$-\dot{h} = -u_s \cos \alpha \sin \theta_b + v_s \sin \phi \cos \theta + u_s \sin \alpha \cos \phi \cos \theta$$

In order to simplify the above equations, the following assumptions were made:

1) Motion in x-z plane only, $\phi = \psi = \beta = v_s = 0$
2) Assume α and θ are small, so that

   $\sin \alpha \cong \alpha \quad \cos \alpha \cong \cos \theta \cong \cos (\alpha + \alpha_T) = 1$

   $\sin \theta \cong \theta$
3) Products of $\dot{\alpha}$, θ, p, and r are negligible.
4) Assume $\dot{u}_s = \dot{V}$ and $V = V_o + \int \dot{V} dt$
5) Thrust component $T \sin (\alpha + \alpha_T)$ is negligible.

Use of these assumptions, which were made in order to use small perturbation theory and three degrees of freedom, resulted in the following simplified equations that were used in the simulation:

$$M_b = I_y \dot{q}_b$$

$$X_s = m \, [\dot{V} + g \, (\theta_b - \alpha)] - T$$

$$Z_s = m \, [-V_o \, (q_b - \dot{\alpha}) - g]$$

$$\dot{\theta}_b = q_b$$

$$-\dot{h} = -V \, (\theta_b - \alpha)$$

The first derivative of the varying quantities can be obtained by rearranging the simplified equations:

$$\dot{q}_b = \frac{M_b}{I_y}$$

$$\dot{V} = \frac{X_s}{m} - g\,(\theta_b - \alpha) + \frac{T}{m} = \frac{1}{m}\,[X_s - mg\,(\theta_b - \alpha) + T]$$

$$\dot{\alpha} = \frac{Z_s}{mV_o} + \frac{g}{V_o} + q_b = \frac{1}{mV_o}\,(Z_s + mg) + q_b$$

$$\dot{\theta}_b = q_b$$

$$\dot{h} = V\,(\theta_b - \alpha)$$

The above equations are the general linearized equations for any aircraft. To simulate a specific aircraft, expressions with the flight characteristics of the aircraft are substituted for X_s, Z_s, and M_b.

B. AERODYNAMIC EQUATIONS

Because the Lockheed T-33 aircraft is used for Combat Readiness Training Flights at the Naval Postgraduate School, it was decided to simulate the T-33 on the modified trainer using data from Ref. 3. The aerodynamic force and moment equations are:

$$X_s = -q_o S(C_{D_o} + C'_{D_\alpha}\alpha + C'_{D_{\alpha^2}}\alpha^2) - q_o S\frac{2}{V_o}(C_{D_o}\Delta V + C'_{D_\alpha}\alpha\Delta V + C'_{D_{\alpha^2}}\alpha^2\Delta V)$$

$$= -(D_o + D_\alpha\alpha + D_{\alpha^2}\alpha^2 + D_{\Delta V}\Delta V + D_{\alpha\Delta V}\alpha\,\Delta V + D_{\alpha^2\Delta V}\alpha^2\Delta V)$$

$$Z_s = -q_o S(C_{L_o} + C_{L_\alpha}\alpha + C_{L_{\delta_E}}\delta_E) - q_o S\frac{2}{V_o}(C_{L_o}\Delta V + C_{L_\alpha}\alpha\Delta V)$$

$$= -(L_o + L_\alpha\alpha + L_{\delta_E}\delta_E + L_{\Delta V}\Delta V + L_{\alpha\Delta V}\alpha\Delta V)$$

$$M_b = I_y(M_\alpha\alpha + M_{\dot\alpha}\dot\alpha + M_q q + M_{\delta_E}\delta_E)$$

Analog diagrams of the equations for simulation are shown in Figures 3, 4, and 5 with the potentiometer settings listed in Table I.

The longitudinal mode was excited with a step input of one degree elevator deflection to test the data, equations, and the analog setup. Results of the positive and negative step functions are shown in Figures 6 and 7. The unrealistic rate of climb indications of 6000 feet per minute after five seconds of elevator deflection and 11,000 to 13,000 feet per minute after ten seconds of deflection suggested an error in the program that could not be found. The phugoid period of 65 seconds observed in the θ response for the negative step input was an acceptable period. The phugoid period for the positive input could not be observed because the computer's amplifiers overloaded after 30 seconds of input. Due to the lack of the actual known results, the obtained results could not be compared to determine the cause of the error. A correct analog setup was verified by comparing the hybrid computer results with results from an IBM 360 computer. Using the same data

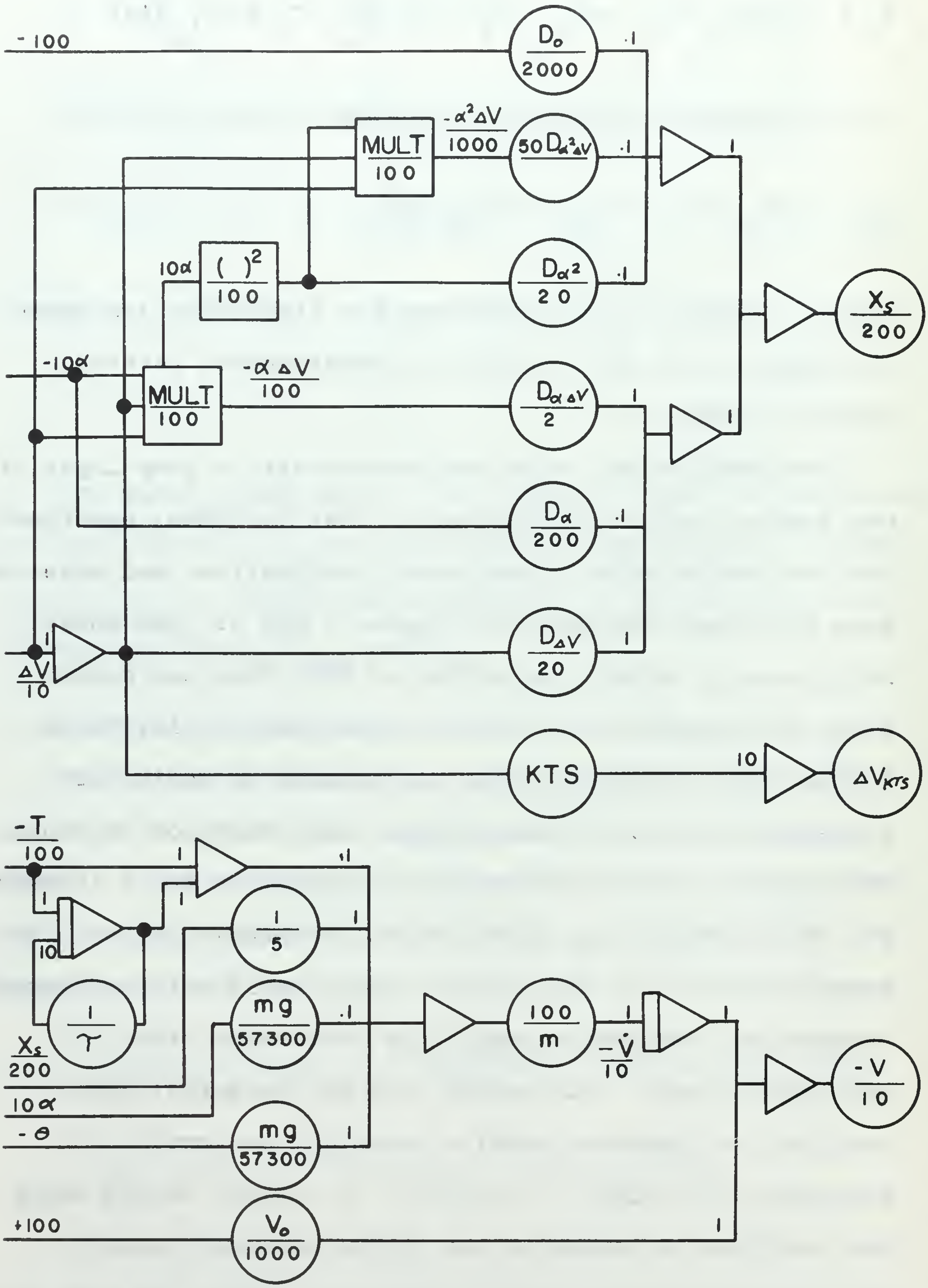

FIGURE 3. ANALOG SIMULATION CIRCUIT (PART I)

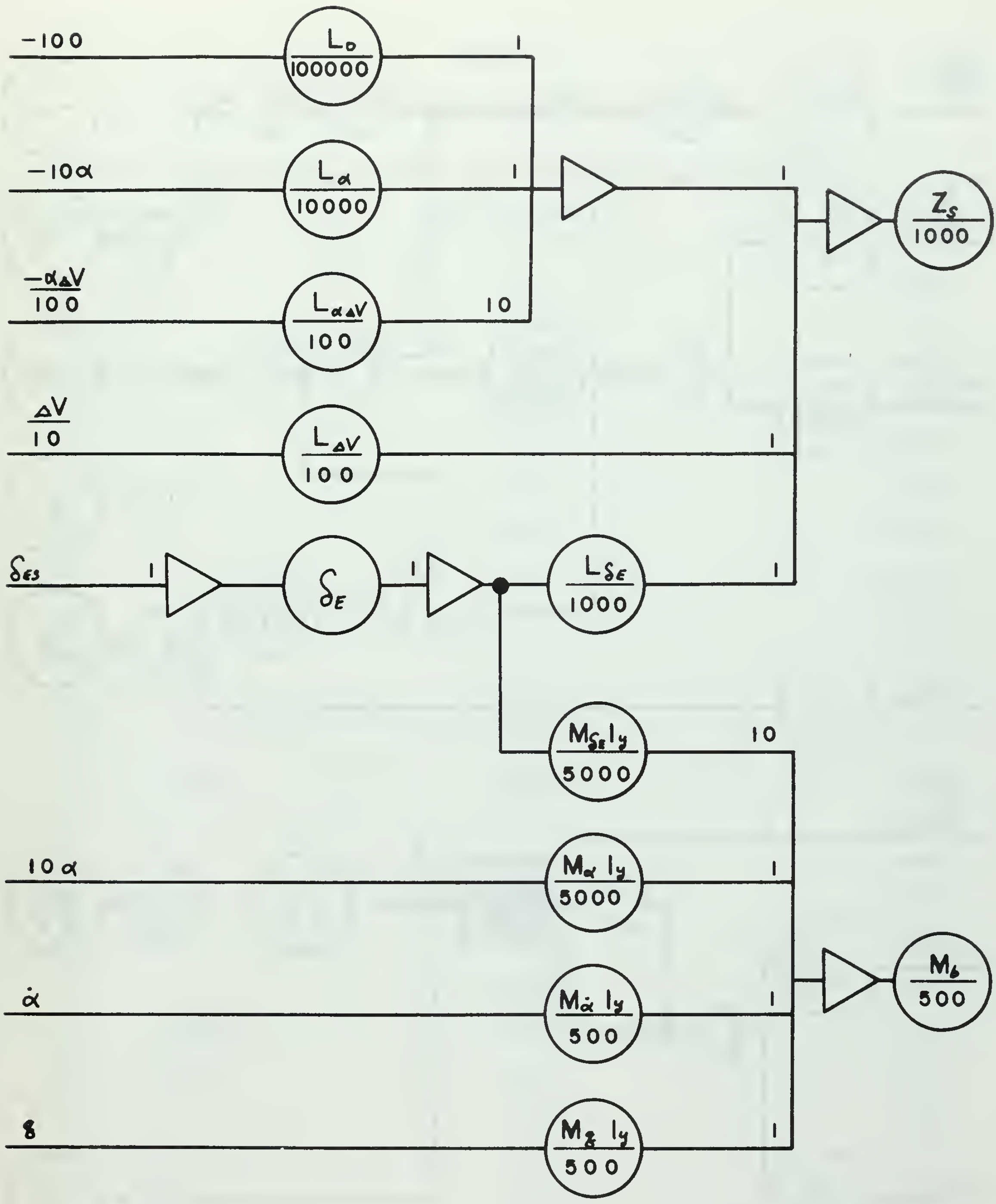

FIGURE 4. ANALOG SIMULATION CIRCUIT (PART 2)

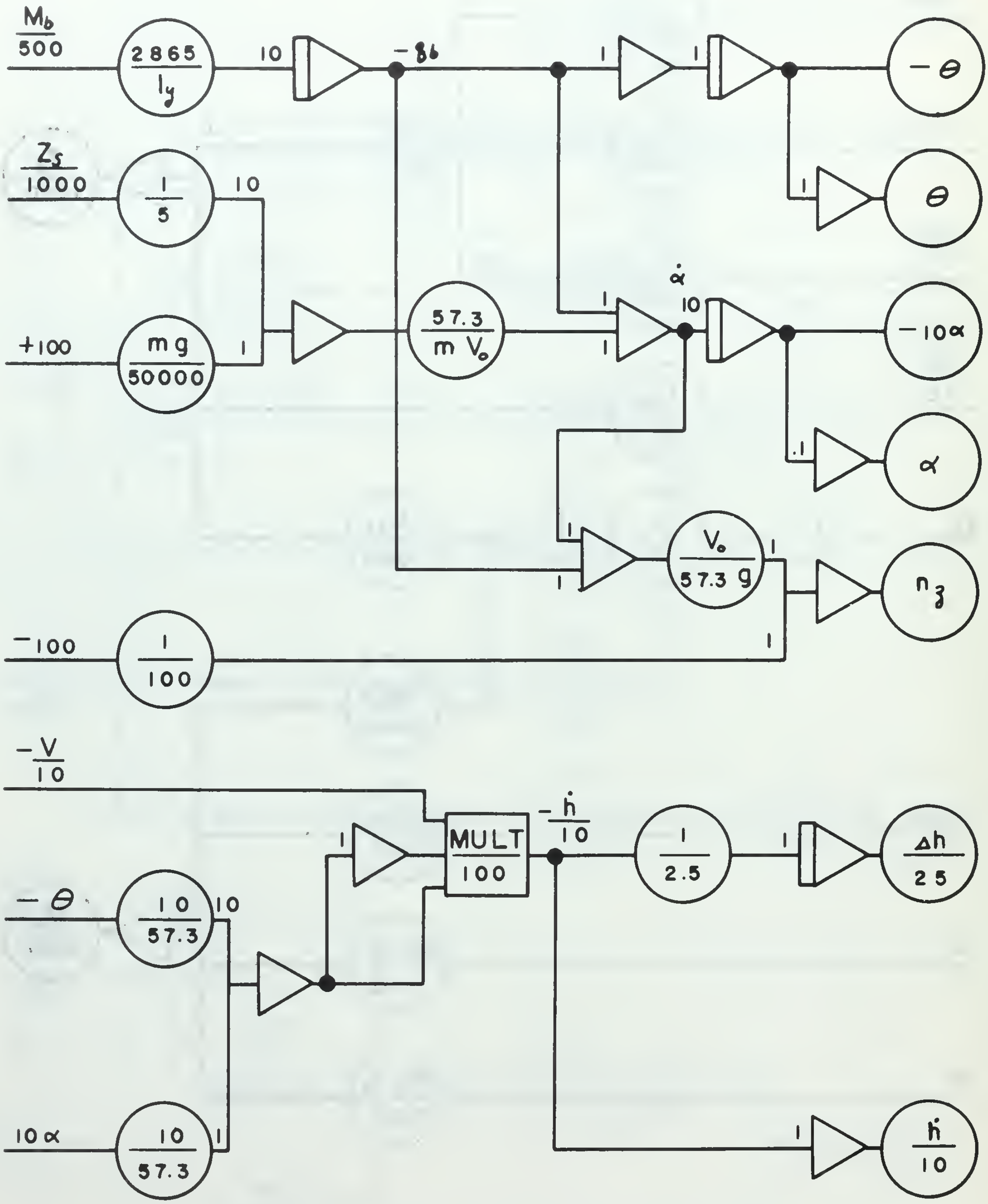

FIGURE 5. ANALOG SIMULATION CIRCUIT (PART 3)

TABLE I

ANALOG POTENTIOMETER SETTINGS

Potentiometer	Reference 3	Reference 5
$D_o/2000$	.5100	.4740
$D_\alpha/200$	.7050	.3635
$D_{\alpha 2}/20$	.0408	.2475
$50D_{\alpha 2 \Delta V}$	.1382	.8100
$D_{\alpha \Delta V}/2$	.2389	.1190
$D_{\Delta V}/20$	.1727	.1550
KTS	.5921	.5921
$1/\tau$	.1000	.1000
1/5	.2000	.2000
mg/57,300	.2164	.2241
$V_o/1000$	.6100	.6130
100/m	.2597	.2507
$L_o/100,000$	.1240	.1284
$L_\alpha/10,000$	.5302	.5650
$L_{\alpha \Delta V}/100$	.1739	.1849
$L_{\Delta V}/100$	.4065	.2955
$L_{\delta E}/1000$	.3016	.3016
δ_E	.1000	.1000
$M_{\delta E}\ I_y/5000$	.9523	.9580
$M_\alpha I_y/5000$	.4877	.7200
$M_{\dot{\alpha}} I_y/500$	.5282	.2050
$M_q I_y/500$	.5318	.4530
$2865/I_y$	.1384	.1384
mg/50,000	.2480	.2568
$57.3/mV_o$	.1221	.1172
$V_o/57.3g$	.3310	.3320
1/100	.0100	.0100
10/57.3	.1745	.1745
1/2.5	.4000	.4000

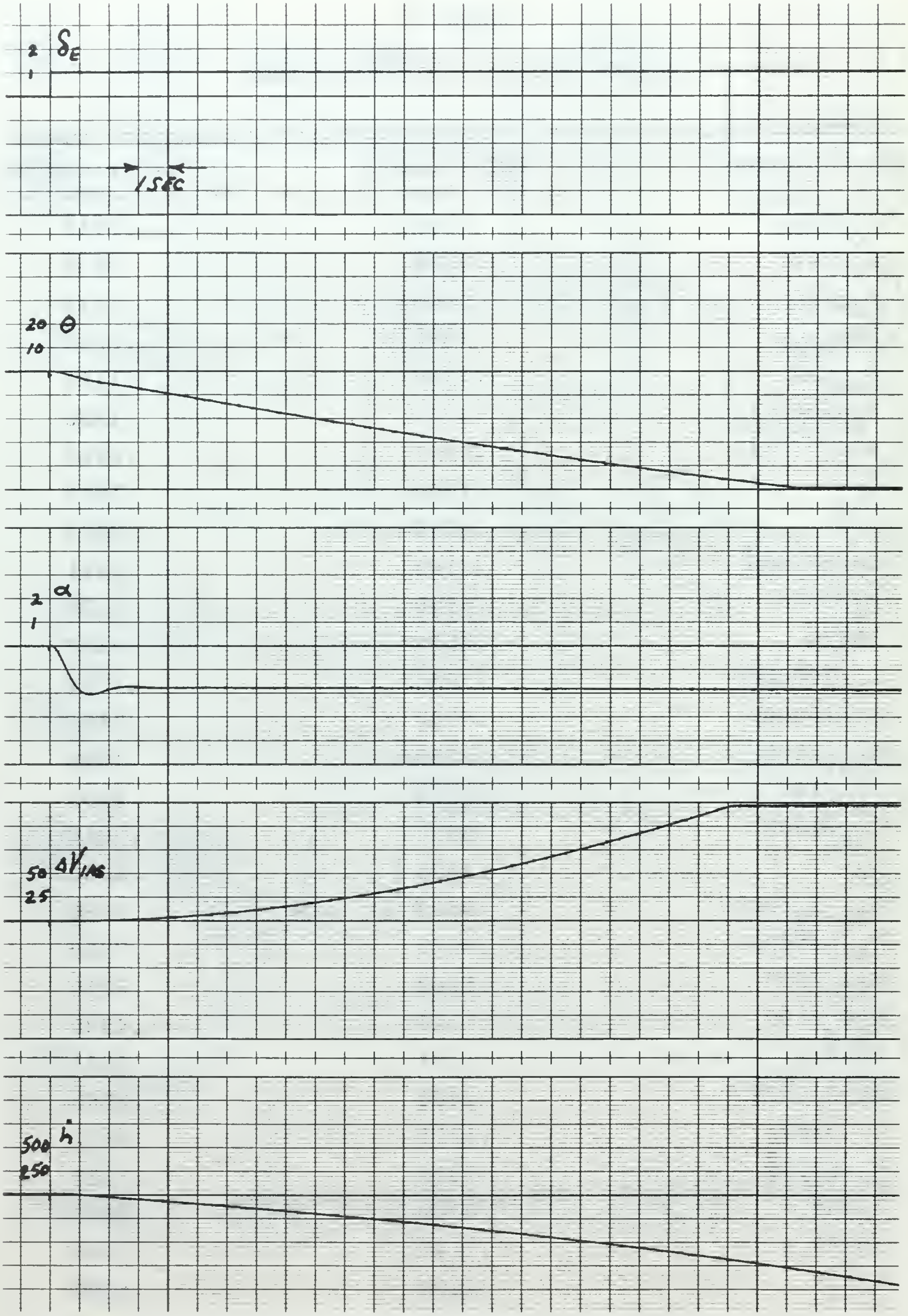

FIGURE 6. RESPONSE TO A POSITIVE ELEVATOR INPUT (Ref. 3 Data)

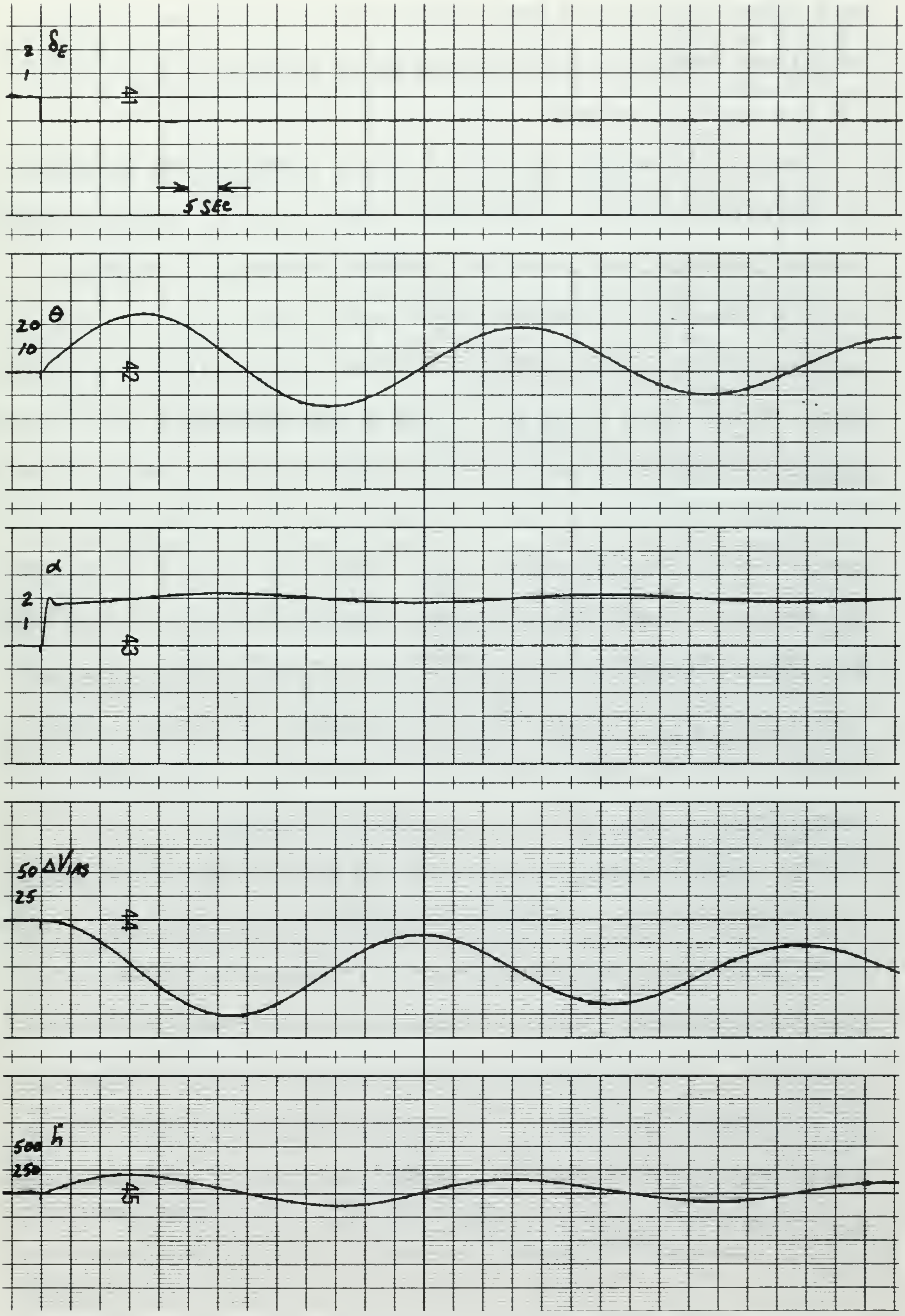

FIGURE 7. RESPONSE TO A NEGATIVE ELEVATOR INPUT (Ref. 3 Data)

and equations in the two computers, the similar results obtained from both of the computers indicated no error in the analog setup.

Data from Refs. 3, 5, and 6 was compared to determine if possible errors in the input data to the computer would cause the obtained results. Minor variations in the initial conditions between the references were not considered significant enough to alter the results. Although most of the data in Refs. 3 and 5 was different, the results shown in Figures 8 and 9, using Ref. 5 data, are not a significant change from the results with data from Ref. 3 shown in Figures 6 and 7. The data from Ref. 5 is listed in Table I. The rate of climb indications were 3,600 feet per minute after five seconds of elevator deflection and 9,000 feet per minute after ten seconds of input. The phugoid period increased to 78 seconds for the negative step input, which is an acceptable response.

In order to use the computer's solutions to the equations of motion for checking the cockpit's instrument movement, the aircraft's characteristics were modified until the positive and negative inputs did not overload the computer. In some cases, the computer solution signal to an instrument was small, so it had to be replaced with a large amplitude sinusoidal signal in order to obtain large instrument dial deflections.

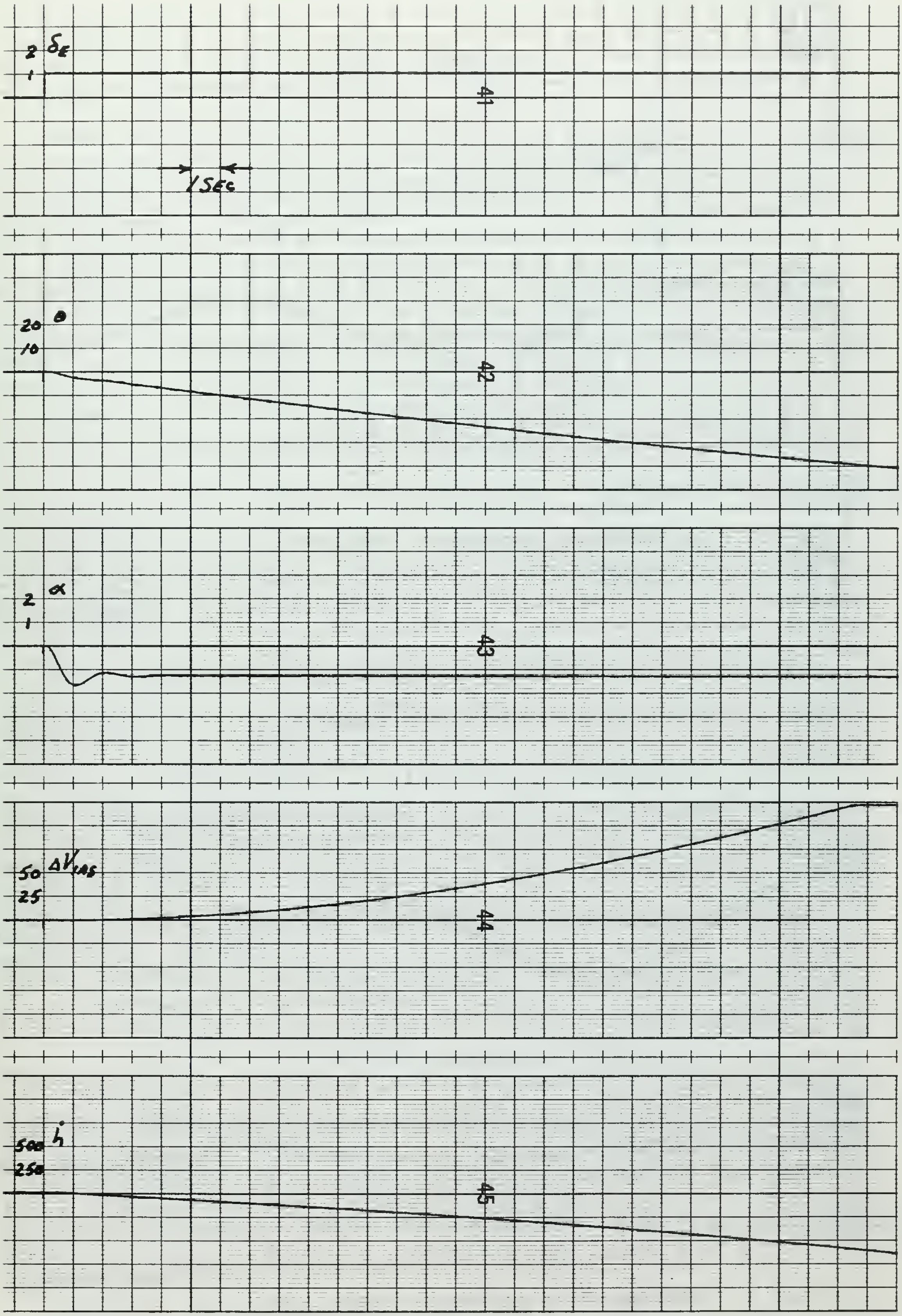

FIGURE 8. RESPONSE TO A POSITIVE ELEVATOR INPUT (Ref. 5 Data)

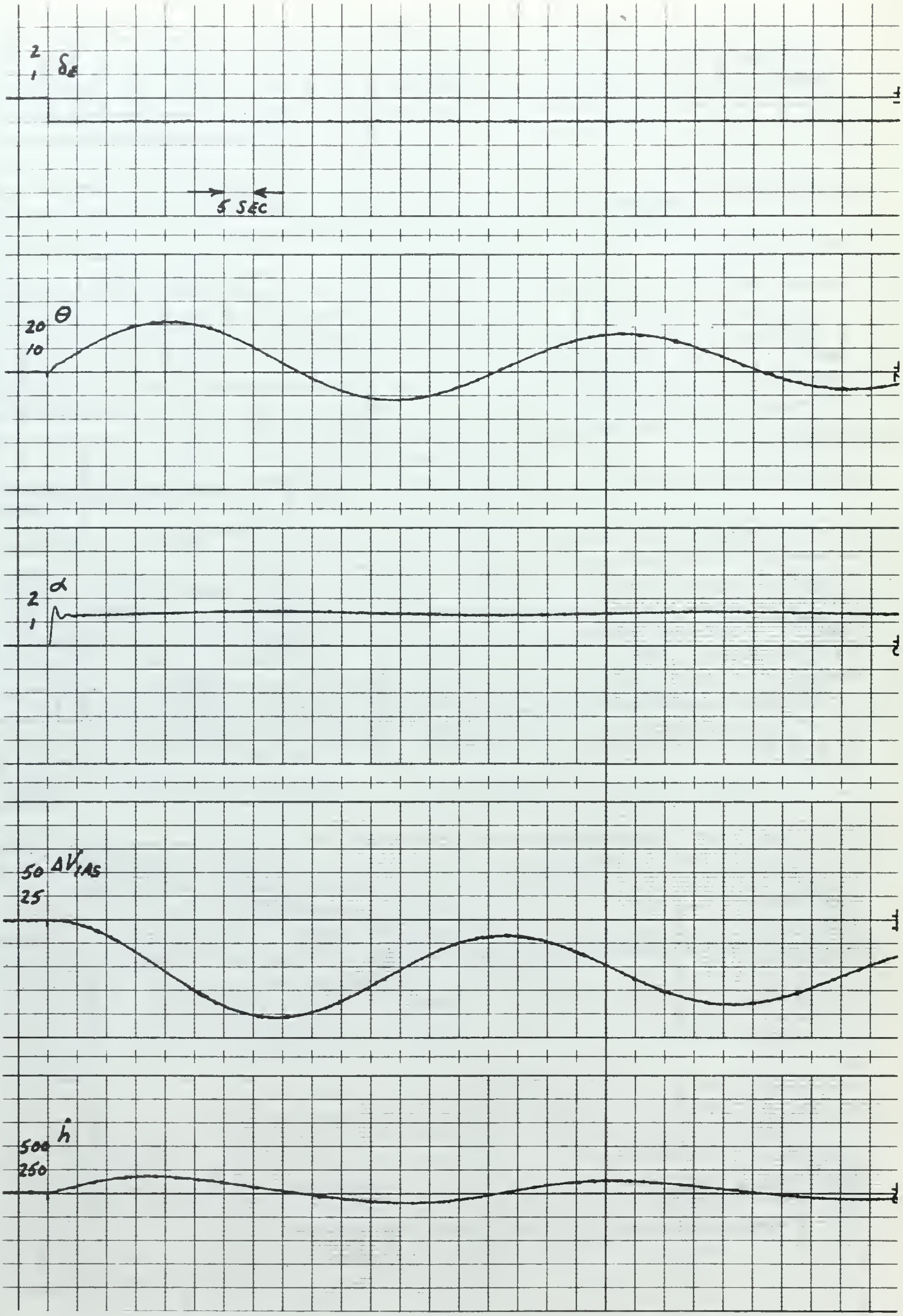

FIGURE 9. RESPONSE TO A NEGATIVE ELEVATOR INPUT (Ref. 5 Data)

III. COCKPIT

The C-11B trainer was modified in two ways: the physical dimensions of the trainer were shortened, and the vacuum tube amplifiers and motor-generators were replaced with solid state devices and dc motors, respectively. The interior of the cockpit remained basically unchanged. The trainer's instruments were retained because of their similarity to present aircraft instruments and the pilot's familiarity with them. The navigation equipment was retained for cockpit realism but was not made operational.

A. CONTROLS

The cockpit of the simulator represents a typical cockpit and has the normal control devices found in most cockpits: control stick for aileron and elevator deflection, foot pedals for rudder deflection, throttle, speed brakes, landing gear, and flaps. The speed brakes, landing gear, and flaps were not connected but provisions were made for their eventual operation. The shortening of the trainer required the linkage for the stick and rudder controls to be altered and relocated in the simulator. Because the elevator portion of the control stick and throttle are the only controls that affect the simulator in the longitudinal mode, they were the only ones considered in this report.

The movement of the linkage for the elevator control had no adverse effect on the force required to control the simulator. The stick force that the pilot must overcome is regulated by a dynamic pressure servo. The servo is presently manually set at a predetermined value but can be programed to vary with altitude and true airspeed. All control force variation due to linkage alteration was absorbed in the dynamic pressure servo setting.

The amount of elevator deflection used in the equations of motion is determined from the stick deflection and the elevator deflection potentiometer at the computer. The deflection of the control stick moves the arm of a tapped potentiometer on the elevator control mechanism and the electric signal is sent to the elevator deflection potentiometer. This potentiometer controls the elevator effectiveness of the simulator by allowing the amount of elevator deflection per unit of stick deflection to be changed. A plot of the signal from the tapped potentiometer versus the stick deflection is shown in Figure 10. The nonlinear portion of the figure was caused by the mechanical linkage in the elevator control mechanism. Because of the improper instrument dial response to a signal from the computer, that will be discussed later, the effect of the stick movement in the equations of motion could not be determined.

The throttle controls the amount of thrust delivered by the simulated engine. Because the engine characteristics

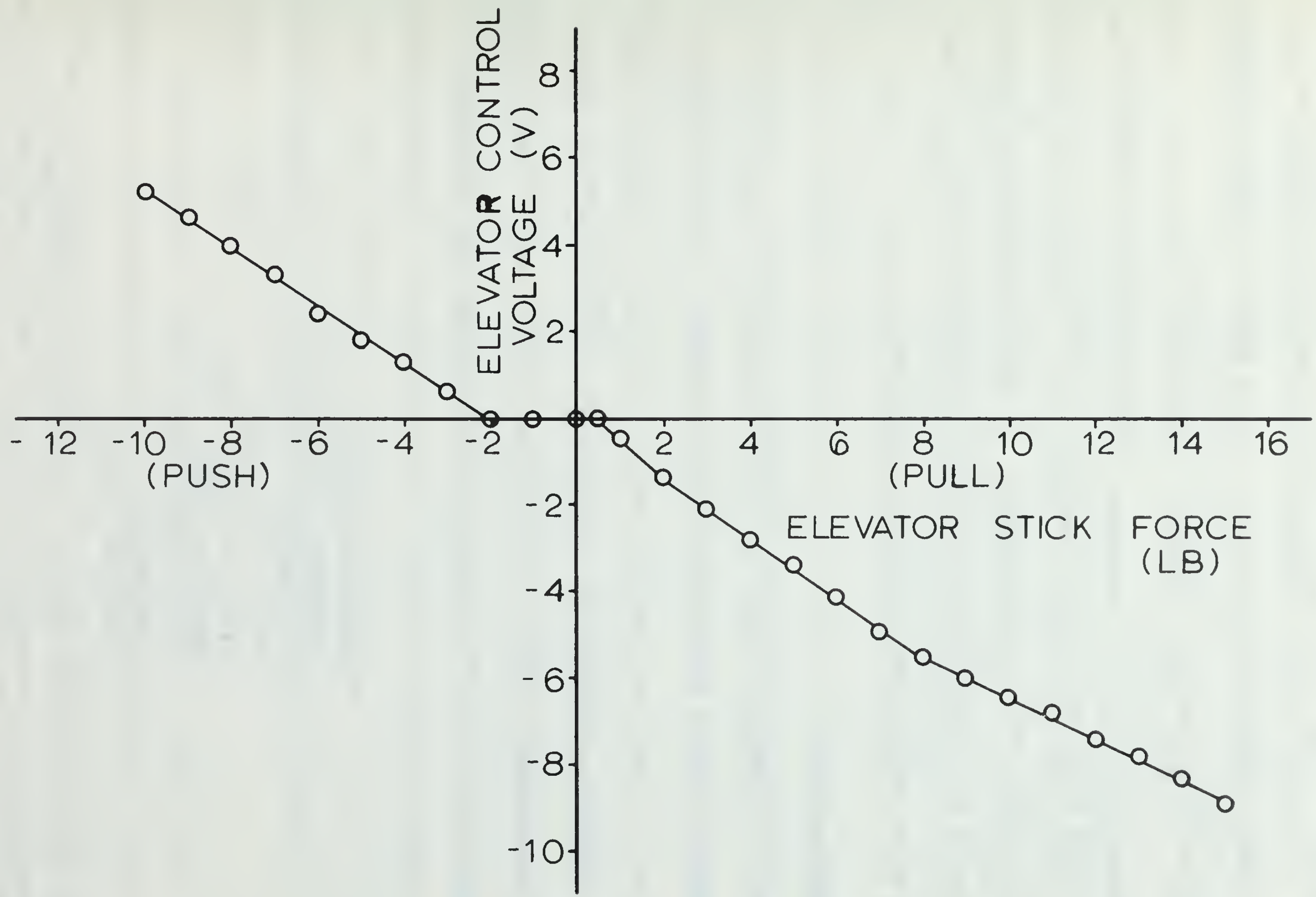

FIGURE 10. ELEVATOR CONTROL STICK CHARACTERISTICS

were not known, the engine was simulated on the computer as having a thrust of 1020 pounds at an altitude of 23,000 feet [Ref. 3]. The engine simulation included a first-order approximation with a one second time constant. The expression for the engine simulation was $T_{computer} = (1-e^{-t/\tau})\ T_{cockpit}$ (where T is the throttle signal and τ is the time constant). The effect of throttle variation was not investigated. A more complete simulation could be accomplished using the digital part of the hybrid when sufficient data is available.

B. INSTRUMENTS

The instruments used in the simulator are typical instruments found in present day aircraft. The driving circuits of the instruments were modified to operate from the dc computer signal by replacing the ac amplifiers and motor-generators with dc motors and solid state amplifiers. Modification of the following instruments was described in Ref. 2:

- accelerometer
- airspeed (indicated)
- altimeter
- angle of attack
- gyro horizon (bank)
- heading (RMI)
- needle and ball
- tachometer
- vertical speed

The gyro horizon (pitch) could not be modified to operate from the dc computer signal, so the dc pitch signal was modified to produce an ac signal. The general

operation of the modified circuit is to attenuate the dc computer signal prior to entrance into the amplifier section. The amplified signal passes through either a P-N-P or a N-P-N transistor and drives a dc motor in the proper direction. The motor, through gear trains, moves the follow-up potentiometer and the synchro transmitter for the instrument. The motor is driven until sufficient voltage from the follow-up potentiometer is directed back to the amplifier to reduce the amplified signal to zero. The synchro receiver in the instrument receives the signal from the synchro transmitter and moves the dial of the instrument. A typical modified circuit is represented by the Modified Airspeed Indicator Drive Circuit shown in Figure 11 [Ref. 2].

The accelerometer, airspeed (indicated), altimeter, angle of attack, vertical speed, and gyro horizon (pitch) instruments were utilized during the longitudinal mode investigation. Because of the lack of valid engine information, the tachometer was not considered. The initial conditions for the instruments and their calibration are shown in Table II.

The motion of the instruments, when a signal was applied, was observed to be erratic and jerky. The nonlinear motion was determined to be caused by the dc motor and the motion of the arm of the follow-up potentiometer. Linear relationships existed between the input signal/attenuated signal and between the synchro transmitter signal/instrument dial. Because the synchro transmitter is

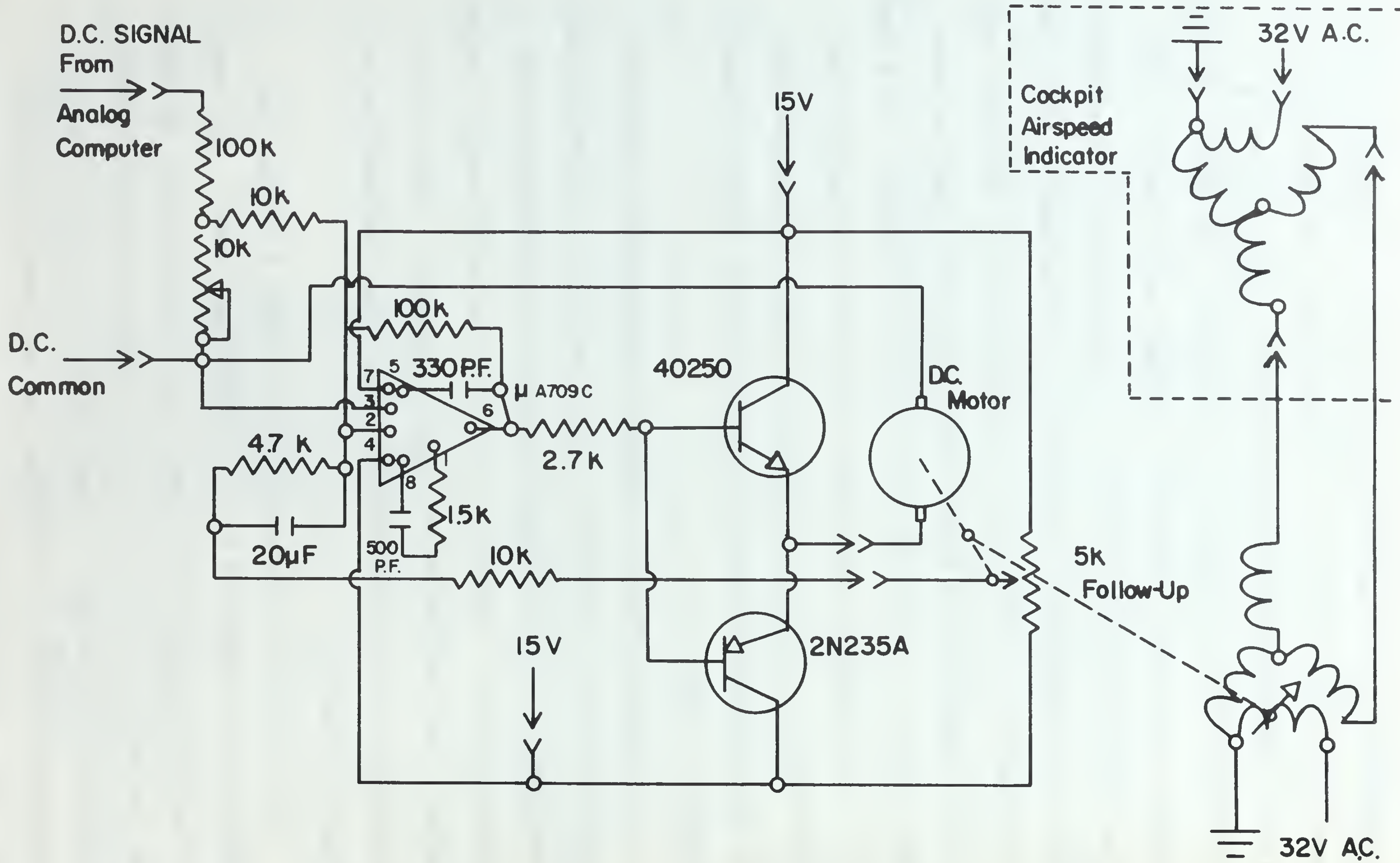

FIGURE 11. MODIFIED AIRSPEED INDICATOR DRIVE CIRCUIT

TABLE II

INITIAL CONDITIONS AND CALIBRATION
OF FLIGHT INSTRUMENTS

Instrument	Initial Condition	Volts D.C.	Calibration
Accelerometer	3.2 g's	+ 100	-0.8 g's
		- 100	+6.5 g's
Airspeed	250 kts.	+ 100	92 kts.
		- 100	405 kts.
Altimeter	23,000 ft.	+ 100	20,030 ft.
		- 100	26,020 ft.
Angle of Attack	12 deg.	+ 100	26 deg.
		- 100	-1 deg.
Gyro Horizon (pitch)	2 deg. up	+ 100	65 deg. up
		- 100	45 deg. down
Vertical Speed	0	+ 100	4000 ft./min. down
		- 100	4200 ft./min. up

connected by gearing to the follow-up potentiometer arm, the voltage from the follow-up potentiometer arm can represent the dial deflection of the instrument. An example of a typical circuit's nonlinear characteristics is shown by the airspeed circuit characteristics in Figure 12.

The dc motor did not react immediately to a signal from the amplifier because of the motor's excitation voltage, stiction, and misalinement of the motor and reduction gear axles; a further delay was noticed in the instrument dial due to gearing backlash. A smaller voltage was required to start the motor rotating when the motor was not attached to the reduction gears than when the motor was attached. The voltage required to start the motor also varied from instrument to instrument because of the degree of misalinement of the motor and reduction gear axles, the number of gears in the gear trains between the motor and the servo transmitter and between the motor and the follow-up potentiometer, and the size of the motor used. Two sizes of dc motors were used because of insufficient amounts of one size.

The motor's nonlinearity was affected by the resolution of the wire-wound follow-up potentiometer [Ref. 4]. The voltage range of the follow-up control was plus 15 volts to minus 15 volts. A small movement of the arm produced a large feedback signal in comparison to the input signal. Reversal of the motor was delayed until sufficient voltage

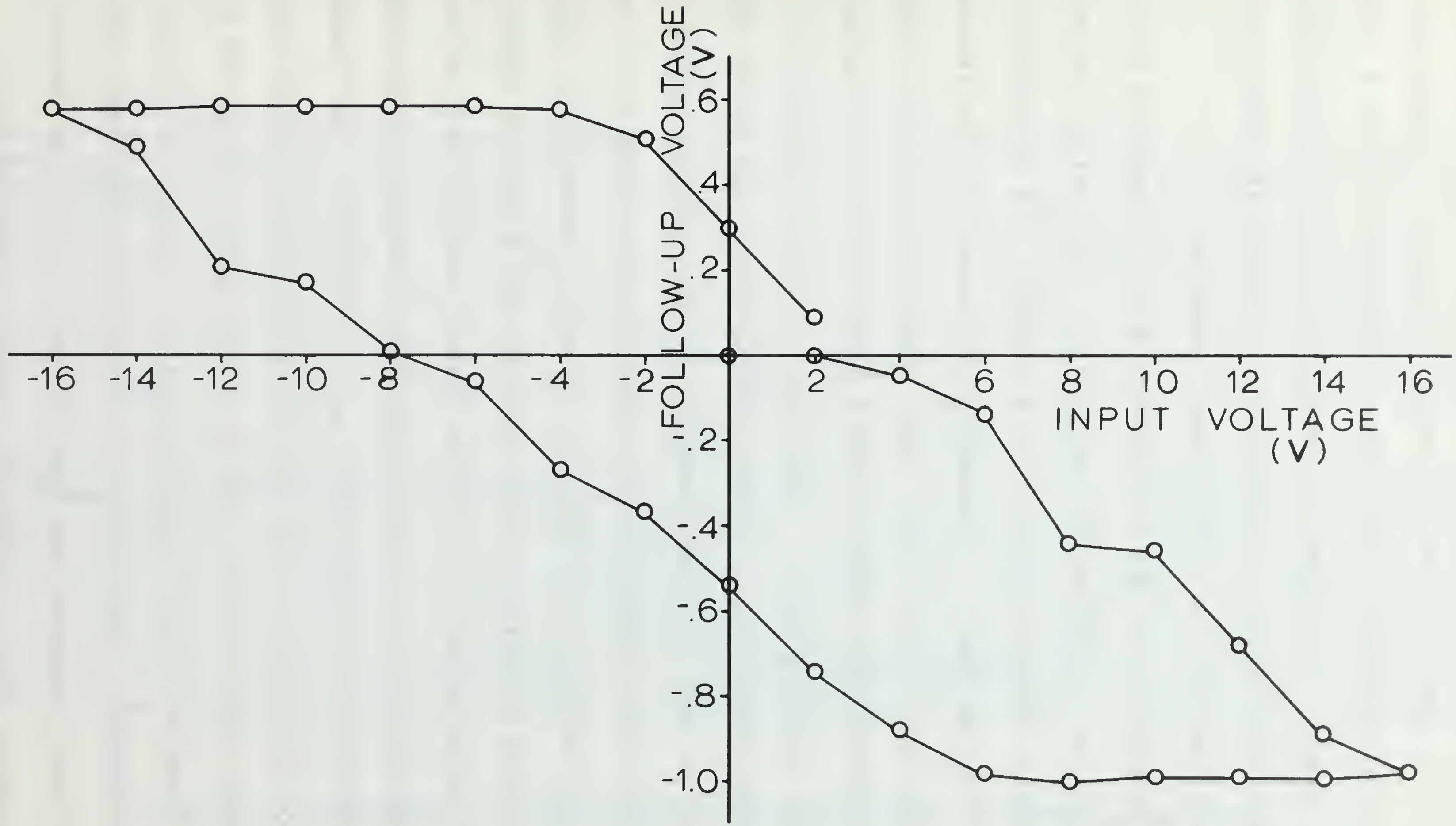

FIGURE 12. AIRSPEED CIRCUIT CHARACTERISTICS

to overcome the backlash was directed to the amplifier by either the input or potentiometer signals. Figure 13 shows the problem of resolution and backlash for a sinusoidal input. A tachometer feedback from the motor was not feasible because the motor's rotation was small once the backlash of the circuit was exceeded.

A reduction in the nonlinearity was attempted by increasing the input to the amplifier, increasing the amplifier gain, adding a bias to the signal, and increasing the follow-up gain. Increasing the ratio of the attenuating resistor to the total input signal resistance resulted in increasing the signal to the amplifier for the same computer input signal. Although this ratio change of resistors resulted in larger movements of the motor shaft, the change was not used because it also caused larger instrument dial deflection. Reducing the amount of instrument dial movement in order to observe incremental dial deflections resulted in the size of the computer input signal being reduced. If the signal was reduced too much, the probability of signal error due to noise was increased.

Increasing the amplifier gain by changing the feedback resistor resulted in the same problems encountered with the increased input signal plus an additional problem by the amplification of the resolution error in the follow-up potentiometer. The addition of a bias voltage was beneficial when movement was restricted to a single direction but hindered the movement of the motor during motor

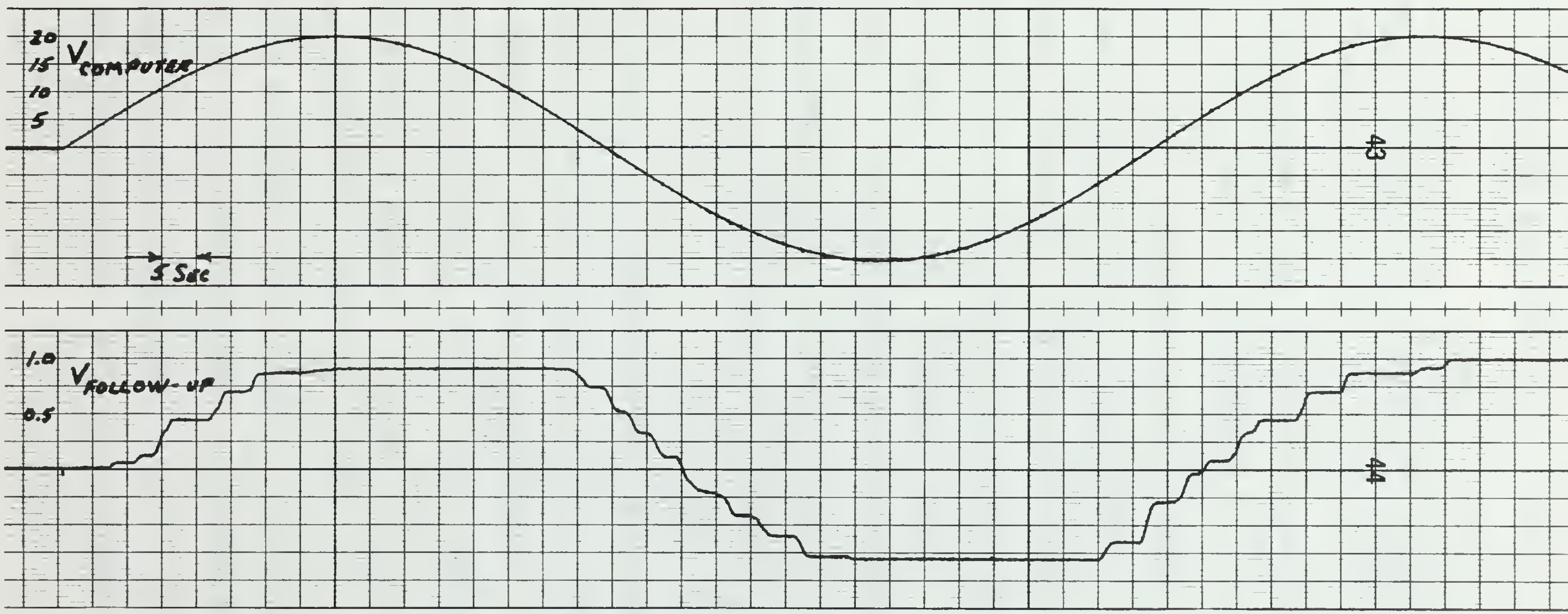

FIGURE 13. COMPARISON OF AIRSPEED SERVO INPUT AND FOLLOW-UP POTENTIOMETER SIGNALS

reversal. An increase in the follow-up potentiometer gain amplified the resolution error and increased the staircase effect of the potentiometer.

The following corrective actions were considered but not implemented because of the lack of time: circuit redesign, decrease of the voltage range of the follow-up potentiometer, and computation of nonlinear describing functions to use in the simulation. The circuit redesign would present a problem in matching the forward and reverse driving voltages to the motor. With the redesign of the gear ratios between the motor/synchro transmitter and the motor/follow-up potentiometer arm, a larger motor shaft rotation could produce a small movement of the instrument dial's synchro transmitter and the follow-up potentiometer arm. This would allow a larger signal to the amplifier for a desired dial deflection.

Decreasing the voltage range on the follow-up potentiometer would require a larger movement of the follow-up arm in order to feedback a sufficient voltage to cancel the input signal. The larger movement would also cause the instrument dial to have a large movement because of the gearing. To obtain the small movements required in the dial deflection, smaller input signals would have to be used which have the problems of signal noise error. The describing function method,in order to take into account the motor's starting voltage, stiction and the

backlash, would be very involved because each circuit has different characteristics.

The nonlinearities might be reduced by acquiring different dc motors that do not require a large starting voltage.

IV. CONCLUSIONS AND RECOMMENDATIONS

The longitudinal flying qualities of the modified C-11B Instrument Flight Trainer are unsatisfactory and do not represent the flying qualities of a present day aircraft. The nonlinear instrument dial movement interferes with the pilot's control of the simulator by requiring extra control movements for a desired maneuver. The lack of accurate instrument indications results in erroneous conclusions by the pilot of the flight characteristics being simulated. Because the lateral direction instruments utilze similar servo circuits as the longitudinal mode, the lateral mode can be assumed to be unsatisfactory, too.

The unrealistic flight data results for the T-33 aircraft requires a "hit or miss" guess at the correct data to be used in the simulation. The conversion of the flight trainer to receive a dc signal from the hybrid computer resulted in a simulator whose aircraft stability derivatives are easily changed.

The versatility of a variable stability simulator for use in demonstrating flight characteristics to academic classes and for providing a research vehicle for the investigation of flying qualities of aircraft, pilot response techniques, new flight instrumentation, and variable-control systems justify the continuation of the modification of the flight trainer. Improvements in the instrument dial representation could be accomplished with

acquisition of low torque dc servo motors, dc potentiometer instruments, or redesign of the present servo motor amplifier circuit. Reliable aircraft data for the T-33 or any single engine jet aircraft is required for proper simulation. The expansion of the equations to six-degrees of freedom with their nonlinear terms is possible with the hybrid computer.

Preliminary indications are that the instabilities of the computer solution lie in the nonlinear terms, such as α^2 and $\alpha\Delta V$. It is recommended that further work in this area be undertaken in two steps; first, eliminate the nonlinear terms and examine the results of the computer solution, and second, investigate the reasons for the unsatisfactory results when the nonlinear terms are used.

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13. ABSTRACT

An investigation of the longitudinal handling qualities of the variable stability flight simulator, converted from a C-11B Instrument Flight Trainer, found the qualities to be an unrealistic representation of aircraft motion. Non-linearities found in the dc servo drive circuits were caused by the dc servo drive motor's starting voltage, stiction, misalinement of the motor and reduction gear axles, potentiometer resolution, and gearing backlash. The equations of motion for the T-33 aircraft were simulated with the analog portion of a hybrid computer.

14 KEY WORDS	LINK A		LINK B		LINK C	
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LONGITUDINAL STABILITY						
AIRCRAFT CONTROL						
HYBRID COMPUTER						